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EVALUATION OF ULTIMATE DISPOSAL METHODS
FOR LIQUID AND SOLID RADIOACTIVE WASTES.

PART III. INTERIM STORAGE OF
SOLIDIFIED WASTES

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OAK RIDGE NATIONAL LABORATORY

operated by

UNION CARBIDE CORPORATION

for the

U.S. ATOMIC ENERGY COMMISSION

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ABSTRACT

The costs of interim storage of solidified Purex and Thorex wastes in water-filled canals were estimated as the third part of a study to evaluate, from the standpoint of economics and hazards, the various steps leading to and including the permanent disposal of highly radioactive liquid and solid wastes. The wastes were assumed to have been solidified following their production in a plant processing 1500 metric tons per year of uranium converter fuel at a burnup of 10,000 Mwd/ton and 270 tons/yr of thorium converter fuel at 20,000 Mwd/ton.

Separate facilities were designed for the storage of the calcined wastes in the acid and reacidified forms, and for the Thorex waste made into a glass. Consideration was given also to storage (in the same facilities) of the combinations acid Purex-acid Thorex and reacidified Purex-reacidified Thorex wastes. Costs for interim storage times from 1 to 30 yr were computed for wastes decayed 120 days and 1, 3, and 10 yr at time of initial storage.

Costs ranged from 1.5×10^{-3} mill/kwh_e for 1-yr storage of calcined 10-yr-old acid Purex waste to 18×10^{-3} mill/kwh_e for 30-yr storage of calcined, reacidified 120-day-old Thorex wastes. Costs of storage of the Purex and Thorex wastes together in the same facility ranged from 1.5×10^{-3} mill/kwh_e for 1-yr storage to 4.8×10^{-3} mill/kwh_e for 30-yr storage for the calcined acid wastes and from 1.8×10^{-3} to 6.3×10^{-3} mill/kwh_e for calcined reacidified wastes. The age of the wastes at time of storage was not a very significant factor, the costs for storage of 10-yr-decayed wastes being only 10 to 15% less than those for storage of the same wastes aged 120 days. Storage of acid wastes as solids was cheaper by factors of 2 to 2.7 than storage

of the same wastes as liquids; however, storage of neutralized liquid wastes was slightly cheaper than storage of reacidified Purex and Thorex solids.

1. INTRODUCTION

This report is one of a series of studies devoted to the engineering, economics, and safety aspects of high-activity waste management.¹⁻³ The intent of these studies is to develop the optimum combination of operations for the management of high-activity wastes from the processing of power reactor fuels and to serve as a guide in directing research and development work currently under way in this field.

As a basis, a 6-metric-ton/day fuel processing plant is assumed, and it would handle the fuel from a 15,000 Mw_e nuclear power economy. ("Tons" in this report refers to metric tons.) This plant would process 1500 tons/yr of uranium converter fuel at a burnup of 10,000 Mwd/ton and 270 tons/yr of thorium converter fuel irradiated to 20,000 Mwd/ton. Management of the resulting Purex and Thorex wastes in both acid and neutralized forms is considered, and of Thorex wastes made into an alumina-silica-borax type glass. In previous studies, conceptual designs and estimated costs were presented for the storage of these wastes as liquids in tanks for times up to 30 yr, and for converting wastes to solids by evaporation to dryness and calcination in stainless steel pots. Costs have also been estimated for shipping the waste-filled pots to permanent disposal sites.

This report presents a conceptual design and cost estimate for interim storage of solidified wastes prior to their shipment and final disposal. Facilities were designed to accommodate the cylinders produced by the pot calcination plant described in a previous study.² In that study, it was assumed that Purex and Thorex wastes were evaporated to dryness and calcined in cylinders 6, 12, and 24 in. in diameter and 10 ft high. Calcination after storage of the wastes as both acid and neutralized solutions was considered as well as production of a glass from acid Thorex waste. The number of cylinders of each size produced annually by processing the wastes in different chemical states is given in Table 1. Only 6-in.-diam vessels were considered for processing Thorex glass.

Table 1. Numbers of Calcination Vessels per year Required for
Wastes from 6-ton/day Processing Plant

Waste Type	Number of Calcination Vessels		
	6-in.-diam	12-in.-diam	24-in.-diam
Acid Purex	925	231	58
Reacidified Purex	2320	580	145
Acid Thorex	1390	348	87
Reacidified Thorex	4110	1028	257
Thorex Glass	1800	-	-

Interim solids storage periods of 1, 3, 10, and 30 yr in water-filled canals were considered for cylinders with contents aged 120 days, 1, 3, and 10 yr at time of filling. In computing the costs, a 4% interest rate was assumed on the capital investment, and the present-worth concept was applied in the case of 30-yr storage where a substantial part of the facility was not immediately needed. Costs were computed for storage of the solidified Purex and Thorex wastes in separate facilities and for joint storage in the same facility.

The assistance of P. L. Robertson in the estimation of costs and structural requirements for cranes and partitions is gratefully acknowledged.

2. DESCRIPTION OF STORAGE AREA

Although the wide range of storage times and waste ages that were considered resulted in storage areas of different sizes and configurations, they consist, in essence, of a central canal for receiving and removing the cylinders, canals for the storage of the cylinders, and a service area containing the water cooling and purification equipment (Fig. 1). An office and change room, not shown in Fig. 1, are also included. The central canal and storage canals are assumed to be constructed of reinforced concrete with perimeter walls and floor 1-ft thick, and inside partitions 2-ft thick. The inside surface of the concrete is painted with a polyamide-cured

Fig. 1. Interim-Storage Canal.

epoxy protective coating as an aid in maintaining high-purity water and for easier decontamination. Coatings of this material are able to withstand radiation dosages of 4.8×10^9 in deionized water before embrittlement and loss of adhesion.⁴ Calculations indicated that, for the cases considered in this study, more than 30 yr would be required for dosage of this magnitude to be accumulated by the coating.

Pertinent data relating to the facilities for the 80 cases considered in this study are summarized in Tables 2a-2d.

2.1 Central Canal

The central canal was designed to receive cylinders of waste from the calcination plant, for storing them briefly for observation of defective cylinders, and for routing them to the proper canal for storage. It also serves as an area for underwater loading of the cylinders into casks prior to shipping off site. This canal is 30 ft wide, 40 ft deep, and ranges in length from 24 to 146 ft, depending on the number and width of the canals (Fig. 2). It is equipped with bridge cranes of 100 tons and 5 tons capacities mounted on track overhead. The larger crane is provided for lifting the shipping casks and can traverse a 40-ft length of track, 20 ft of which extends over the canal. The 5-ton crane, operable over the remaining central canal area, is for manipulating the individual cylinders under water.

2.2 Storage Canals

The cylinders of solidified waste are assumed to be stored upright in canals adjoining the central facility. It is assumed that they were arranged in parallel rows, each row consisting of two cylinders staggered back-to-back, with a space between rows for moving them in and out. With this arrangement, each cylinder is allowed a space 1.5 times its diameter along the row and twice its diameter across the row, permitting in the case of a 48-ft-wide canal, 24 rows of 6-in.-diam cylinders, 12 rows of 12-in.-diam cylinders, or 6 rows of 24-in.-diam cylinders. The length of canal required for storage of the cylinders in this array is a function only of interim storage time and is independent of the diameter of the cylinder. The lengths of 48-ft-wide canal required for the various waste types for different storage times vary from 14.5 ft

Table 2a. Description of Facilities for One Year's Storage of Solidified Wastes

Waste Type and Age (yr) at Time of Storage	Excavation (yd ³)	Concrete (yd ³)	Inside Surfaces Concrete (ft ²)	1/4-in. Aluminum Plate Partitions (ft ²)	Max. Heat Evolution (10 ⁶ Btu/hr)	5-ton Bridge Cranes		Capacity Demineralizer System (gpm)	Radiation Monitors (Number)	Floor Area Buildings (ft ²)	
						(Number)	Length Double Track (ft)			Central Facility, Services, Office	Storage Canals
Acid Purex											
0.33	2150	343	8980	1650	23.0	1	29	36	3	3200	1060
1	2130	339	8880	1600	10.5	1	29	36	3	3200	1060
3	2090	334	8760	1530	3.87	1	29	36	3	3200	1060
10	2040	327	8570	1430	1.37	1	29	36	3	3200	1060
Reacidified Purex											
0.33	4580	652	17,200	5040	23.0	3	36	79	12	5080	2460
1	4520	643	17,000	4880	10.5	3	36	79	12	5080	2460
3	4430	634	16,700	4660	3.87	3	36	79	12	5080	2460
10	4280	622	16,200	4320	1.37	3	36	79	12	5080	2460
Acid Thorex											
0.33	2630	440	11,500	2440	8.30	2	44	43	6	3200	1600
1	2590	433	11,300	2360	3.78	2	44	43	6	3200	1600
3	2530	425	11,100	2240	1.39	2	44	43	6	3200	1600
10	2450	412	10,700	2080	0.49	2	44	43	6	3200	1600
Reacidified Thorex											
0.33	5920	747	19,800	8580	8.30	3	64	107	12	5120	4000
1	5810	737	19,500	8320	3.78	3	64	107	12	5120	4000
3	5670	723	19,100	7940	1.39	3	64	107	12	5120	4000
10	5440	701	18,600	7360	0.49	3	64	107	12	5120	4000
Thorex glass											
0.33	2950	528	12,400	3080	8.30	2	64	49	6	5080	2000
1	2900	521	12,200	2980	3.78	2	64	49	6	5080	2000
3	2820	510	12,000	2830	1.39	2	64	49	6	5080	2000
10	2720	496	11,600	2630	0.49	2	64	49	6	5080	2000

Table 2b. Description of Facilities for Three Years' Storage of Solidified Wastes

Waste Type and Age (yr) at Time of Storage	Excavation (yd ³)	Concrete (yd ³)	Inside Surfaces Concrete (ft ²)	1/4-in. Aluminum Plate Partitions (ft ²)	Max. Heat Evolution (10 ⁶ Btu/hr)	5-ton Bridge Cranes		Capacity Demineralizer System (gpm)	Radiation Monitors (Number)	Floor Area Buildings (ft ²)	
						(Number)	Length Double Track (ft)			Central Facility, Services, Office	Storage Canals
Acid Purex											
0.33	5030	689	18,200	6270	35.0	3	44	86	12	5040	2920
1	4960	679	17,900	6070	18.9	3	44	86	12	5040	2920
3	4850	666	17,600	5810	8.37	3	44	86	12	5040	2920
10	4700	647	17,100	5410	3.97	3	44	86	12	5040	2920
Reacidified Purex											
0.33	10,400	1373	37,000	20,200	35.0	5	288	187	12	5400	8820
1	10,100	1348	36,300	19,500	18.9	5	288	187	12	5400	8820
3	9810	1313	35,400	18,600	8.37	5	288	187	12	5400	8820
10	9290	1260	33,900	17,300	3.97	5	288	187	12	5400	8820
Acid Thorex											
0.33	5920	747	20,100	8860	12.6	3	64	107	12	5120	4000
1	5810	737	19,800	8580	6.81	3	64	107	12	5120	4000
3	5670	723	19,300	8160	3.01	3	64	107	12	5120	4000
10	5440	701	18,800	7580	1.43	3	64	107	12	5120	4000
Reacidified Thorex											
0.33	18,400	1899	50,400	34,300	12.6	5	256	340	24	9680	14,400
1	18,000	1869	49,700	33,300	6.81	5	256	340	24	9680	14,400
3	17,500	1828	48,600	31,700	3.01	5	256	340	24	9680	14,400
10	16,600	1767	47,000	29,400	1.43	5	256	340	24	9680	14,400
Thorex glass											
0.33	8550	1171	31,400	12,300	12.6	5	224	154	12	5010	7000
1	8400	1149	30,900	11,900	6.81	5	224	154	12	5010	7000
3	8100	1118	30,000	11,300	3.01	5	224	154	12	5010	7000
10	7700	1075	28,900	10,500	1.43	5	224	154	12	5010	7000

Table 2c. Description of Facilities for Ten Years' Storage of Solidified Wastes

Waste Type and Age (yr) at Time of Storage	Excavation (yd ³)	Concrete (yd ³)	Inside Surfaces. Concrete (ft ²)	1/4-in. Aluminum Plate Partitions (ft ²)	Max. Heat Evolution (10 ⁶ Btu/hr)	5-ton Bridge Cranes		Capacity Demineralizer System (gpm)	Radiation Monitors (Number)	Floor Area Buildings (ft ²)	
						(Number)	Length Double Track (ft)			Central Facility, Services, Office	Storage Canals
Acid Purex											
0.33	13,100	1679	17,200	21,900	47.0	5	384	234	12	5560	9600
1	12,800	1651	17,000	21,200	30.9	5	384	234	12	5560	9600
3	12,400	1605	16,700	20,300	18.5	5	384	234	12	5560	9600
10	11,700	1542	16,300	18,900	11.8	5	384	234	12	5560	9600
Reacidified Purex											
0.33	31,200	2834	76,000	67,800	47.0	5	484	568	24	10,500	26,400
1	30,400	2789	74,800	65,600	30.9	5	484	568	24	10,500	26,400
3	29,300	2728	73,200	62,700	18.5	5	484	568	24	10,500	26,400
10	27,600	2634	70,400	58,100	11.8	5	484	568	24	10,500	26,400
Acid Thorex											
0.33	20,600	2054	54,400	39,900	16.9	5	288	372	24	9800	16,200
1	20,000	2024	53,600	38,600	11.1	5	288	372	24	9800	16,200
3	19,300	1974	52,500	36,700	6.69	5	288	372	24	9800	16,200
10	18,300	1904	50,800	34,100	4.26	5	288	372	24	9800	16,200
Reacidified Thorex											
0.33	48,800	4934	112,000	114,000	16.9	5	852	927	24	11,800	46,000
1	47,700	4124	111,000	111,000	11.1	5	852	927	24	11,800	46,000
3	45,900	4024	108,000	106,000	6.69	5	852	927	24	11,800	46,000
10	42,900	3894	104,000	98,000	4.26	5	852	927	24	11,800	46,000
Thorex glass											
0.33	25,100	2384	71,600	51,700	16.9	5	376	460	24	10,100	20,800
1	24,400	2344	62,400	50,000	11.1	5	376	460	24	10,100	20,800
3	23,500	2294	61,200	47,500	6.69	5	376	460	24	10,100	20,800
10	22,200	2214	59,200	44,200	4.26	5	376	460	24	10,100	20,800

Table 2d. Description of Facilities for Thirty Years' Storage of Solidified Wastes

Waste Type and Age (yr) at Time of Storage	Excavation (yd ³)	Concrete (yd ³)	Inside Surfaces Concrete (ft ²)	1/4-in. Aluminum Plate Partitions (ft ²)	Max. Heat Evolution (10 ⁶ Btu/hr)	5-ton Bridge Cranes		Capacity Demineralizer System (gpm)	Radiation Monitors (Number)	Floor Area Buildings (ft ²)	
						(Number)	Length Double Track (ft)			Central Facility, Services, Office	Storage Canals
Acid Purex											
0.33	36,700	3224	36,000	82,100	68.0	5	576	660	24	10,800	31,400
1	35,700	3174	84,800	79,500	52.6	5	576	660	24	10,800	31,400
3	34,400	3104	82,800	76,000	38.6	5	576	660	24	10,800	31,400
10	31,800	2994	80,400	70,800	28.2	5	576	660	24	10,800	31,400
Reacidified Purex											
0.33	82,500	6594	177,000	202,000	68.0	5	1444	1520	24	13,900	77,400
1	80,300	6484	174,000	196,000	52.6	5	1444	1520	24	13,900	77,400
3	77,000	6344	170,000	187,000	38.6	5	1444	1520	24	13,900	77,400
10	71,800	6214	164,000	173,000	28.2	5	1444	1520	24	13,900	77,400
Acid Thorex											
0.33	50,300	4264	115,000	120,000	24.5	5	864	942	24	11,800	48,600
1	48,800	4194	113,000	116,000	18.9	5	864	942	24	11,800	48,600
3	47,000	4094	111,000	110,000	13.9	5	864	942	24	11,800	48,600
10	44,000	3944	107,000	102,000	10.2	5	864	942	24	11,800	48,600
Reacidified Thorex											
0.33	126,000	10,180	273,000	309,000	24.5	7	2304	2420	36	20,900	103,400
1	123,000	10,020	269,000	299,000	18.9	7	2304	2420	36	20,900	103,400
3	118,000	9790	263,000	286,000	13.9	7	2304	2420	36	20,900	103,400
10	110,000	9440	254,000	265,000	10.2	7	2304	2420	36	20,900	103,400
Thorex glass											
0.33	64,400	5284	142,000	154,000	24.5	5	1124	1200	24	12,800	60,400
1	62,500	5214	139,000	149,000	18.9	5	1124	1200	24	12,800	60,400
3	59,900	5084	136,000	142,000	13.9	5	1124	1200	24	12,800	60,400
10	56,200	4904	131,000	132,000	10.2	5	1124	1200	24	12,800	60,400

Fig. 2. Layouts of Central Canal and Storage Canals for Various Waste Types and Interim Storage Times.

for 1-yr storage of acid Purex to 1920 ft for 30-yr storage of reacidified Thorex (Table 3).

Table 3. Lengths (ft) of 48-ft-Wide Canal Required for Interim Storage of Different Waste Types as Solids

Type of Waste	Interim Storage Time (yr)			
	1	3	10	30
Acid Purex	14.5	43.3	145	433
Reacidified Purex	36.2	108	362	1085
Acid Thorex	21.7	65.0	217	650
Reacidified Thorex	64.1	192	640	1920
Thorex Glass	28.1	84.5	281	845

In designing the canals, the total lengths are broken into more practical and economically-sized segments, with widths either 48 or 24 ft, each abutting on the central canal (Fig. 2). Widths greater than 48 ft are considered undesirable from the standpoint of spanning with bridge cranes. To provide for drainage and maintenance, 25% excess capacity is added to the storage canals, and each segment is sized to handle no more than 25% of the total cylinders, except in those cases where the central canal is larger than a segment. In the latter instances, it is assumed that the central facility will serve as a temporary storage area while a canal is out of service.

To maintain them in position during storage, the cylinders are placed in individual stands, approximately 4-1/2 ft high, constructed of a structural aluminum alloy and anchored in the floor (Fig. 3). The cylinders are placed in and removed from these stands by use of an overhead 5-ton bridge crane, one for each canal segment.

Fig. 3. Stand for Support of Cylinders During Storage.

The depth of the canals is determined by the thickness of water needed for shielding and by the height of the cylinders. The thickness of water required to attenuate the radiation field to 0.25 mr/hr at the surface was computed, assuming infinite slab geometry, as a function of age for the various waste types (Fig. 4). The shielding requirements varied from 15.4 ft for 120-day-old acid Purex to 10 ft for 10-yr-old reacidified Thorex. Details of this calculation can be found in Appendix A. The shielding thickness, added to a fixed depth of 13 ft for cylinder height and free-board, determined the total depth.

As an aid in locating defective cylinders during storage, the canals are provided with vertical partitions along their length, spaced 8 ft apart, and fabricated of 1/4-in.-thick aluminum plate. These partitions serve to channel the water entering the storage canals from the central canal and reduce cross-mixing. As it leaves the canals, the water in each channel is continuously monitored for radioactivity by a Geiger tube detector with a recorder and an alarm. These detectors can reproducibly sense beta and gamma activity in the range of 25 counts/min above background. In these facilities, this would correspond to an activity leak rate of 20 to 600 millicuries/day of Sr-Y⁹⁰ or Cs-Ba¹³⁷. Should contamination of water along a channel be noted, individual cylinders in that channel can be monitored by lowering a 12- to 15-ft-long tube over the cylinder and pumping a small stream of water from inside this shroud through a portable scintillation detector. Once isolated, the defective cylinder can be returned to the calcination plant for repair.

In the event of serious contamination of a canal or the need for major maintenance, a canal can be drained by constructing a temporary bulkhead across the 4-ft-wide opening between that canal and the central canal. The bulkhead consists of segments of steel plate or heavy timber, dropped into position by one of the overhead cranes.

The storage canals are housed in a light-construction steel building to reduce littering and to make operation in inclement weather less difficult.

Fig. 4. Thickness of Water Shielding Required to Reduce Radiation Dosage to 0.25 mr/hr, as a Function of Type and Age of Waste.

2.3 Service Area

The canal water is recycled to the service area for cooling and demineralization. The cooling system consists of pumps, intermediate heat exchangers, and a cooling tower. In the primary loop, water is circulated by pumping from the ends of the canals, through the heat exchangers, and back to the central facility. In the secondary loop, cooling water is pumped through the heat exchangers and returned to the cooling tower. Cooling systems are designed to handle the maximum heat generation rates for Purex and Thorex wastes of different ages and for various storage times (Tables 2a-2d). A temperature rise of 26 to 28°F of the water during passage through the canals is allowed. These rates vary from 4.9×10^5 Btu/hr for the case of 1-yr storage of 10-yr-decayed Thorex waste to 6.8×10^7 Btu/hr for 30-yr storage of 1/3-yr-decayed Purex wastes. An explanation of how they were computed is presented in Appendix B.

The water purification equipment consists of a filter and deionizers through which the water in the canals is circulated at a rate equivalent to a turnover time of one week. The water is deionized by passing first through a bed of strongly acid resin, and then through a bed of weakly basic resin. Tanks are provided for the storage of acid and sodium carbonate regenerating solutions. Flow rates through this system for the different cases vary from 36 gpm for 1-yr storage of acid Purex waste to 2420 gpm for 30-yr storage of reacidified Thorex (Tables 2a-2d).

A masonry building is provided to house the water purification system, a small maintenance shop, office, and change room. The building also encloses the central canal.

3. COSTS

Costs are estimated for each of the 80 facilities designed for storage of the different waste types as a function of waste age and duration of storage (Tables 4a-4d). The total costs, composed of capital and operating costs, are expressed both as dollars per year and mills per electrical kilowatt-hour. These results are then used to estimate costs for the joint storage of the Purex and Thorex wastes calcined in the acid and in the reacidified forms.

Table 4a. Costs for One Year's Storage of Solidified Wastes

Waste Type and Age (yr) at Time of Storage	Excavation (\$/yr)	Concrete (\$/yr)	Epoxy Lining (\$/yr)	Al Partitions (\$/yr)	Cooling System (\$/yr)	Cranes (\$/yr)	Demineralizer (\$/yr)	Radiation Monitors (\$/yr)	Buildings (\$/yr)	Const. O'head, Eng. and Contingency (\$/yr)	Total Capital (\$/yr)	Total Capital & Operating (\$/yr) (10 ⁻³ mills/kwh _e)
Acid Purex												
0.33	100	1590	1380	530	20,500	8400	1800	600	4000	29,200	68,100	181,000 1.86
1	100	1580	1370	510	9900	8400	1800	600	4000	21,200	49,500	163,000 1.68
3	95	1550	1350	490	4200	8400	1800	600	4000	16,900	39,400	152,000 1.56
10	95	1520	1320	460	2000	8400	1800	600	4000	15,100	35,300	148,000 1.52
Reacidified Purex												
0.33	210	3030	2630	1610	20,500	9800	3900	1700	6500	37,400	87,300	200,000 2.06
1	210	2990	2620	1560	9900	9800	3900	1700	6500	28,800	68,000	182,000 1.87
3	205	2950	2570	1490	4200	9800	3900	1700	6500	15,000	58,300	171,000 1.76
10	200	2890	2490	1380	2000	9800	3900	1700	6500	23,200	54,100	167,000 1.72
Acid Thorex												
0.33	120	2050	1770	780	8000	8700	2100	1000	4100	21,400	50,000	163,000 4.66
1	120	2010	1740	750	4100	8700	2100	1000	4100	18,400	43,000	156,000 4.46
3	115	1980	1710	720	2000	8700	2100	1000	4100	16,800	39,200	152,000 4.35
10	115	1910	1650	660	1500	8700	2100	1000	4100	16,300	38,000	151,000 4.32
Reacidified Thorex												
0.33	275	3470	3050	2750	8000	9800	5300	1700	6900	30,900	72,100	185,000 5.29
1	270	3430	3000	2660	4100	9800	5300	1700	6900	27,900	65,100	178,000 5.09
3	265	3360	2940	2540	2000	9800	5300	1700	6900	26,100	60,900	174,000 4.98
10	250	3260	2860	2350	1500	9800	5300	1700	6900	25,400	59,300	172,000 4.92
Thorex glass												
0.33	135	2450	1910	980	8000	8800	2400	1000	6400	24,100	56,200	169,000 4.83
1	135	2420	1880	950	4100	8800	2400	1000	6400	21,100	49,000	162,000 4.63
3	130	2370	1850	900	2000	8800	2400	1000	6400	19,400	45,300	158,000 4.52
10	125	2310	1790	840	1500	8800	2400	1000	6400	18,900	44,100	157,000 4.49

Table 4b. Costs for Three Years' Storage of Solidified Wastes

Waste Type and Age (yr) at Time of Storage	Excavation (\$/yr)	Concrete (\$/yr)	Epoxy Lining (\$/yr)	Partitions (\$/yr)	Cooling System (\$/yr)	Cranes (\$/yr)	Demineralizer (\$/yr)	Radiation Monitors (\$/yr)	Buildings (\$/yr)	Const. O'head, Eng. and Contingency (\$/yr)	Total Capital (\$/yr)	Total Capital & Operating (\$/yr) (10 ⁻³ mills/kwh _e)
Acid Purex												
0.33	230	3200	2800	2000	31,000	9800	4200	1700	6600	46,500	108,000	221,000 2.28
1	230	3160	2760	1940	17,000	9800	4200	1700	6600	35,500	82,900	196,000 2.02
3	225	3100	2710	1860	8000	9800	4200	1700	6600	28,600	66,800	180,000 1.85
10	220	3010	2630	1730	4300	9800	4200	1700	6600	25,600	59,800	173,000 1.78
Reacidified Purex												
0.33	480	6380	5700	6460	31,000	10,800	9200	1700	8300	60,000	140,000	253,000 2.60
1	470	6270	5590	6240	17,000	10,800	9200	1700	8300	49,400	115,000	228,000 2.35
3	460	6100	5450	5950	8000	10,800	9200	1700	8300	42,000	98,000	211,000 2.17
10	430	5860	5220	5540	4300	10,800	9200	1700	8300	38,500	89,900	203,000 2.09
Acid Thorex												
0.33	270	3470	3090	2830	11,700	9800	5300	1700	6900	33,800	78,900	192,000 5.49
1	270	3430	3050	2740	6700	9800	5300	1700	6900	29,900	69,800	183,000 5.23
3	260	3360	2970	2610	3400	9800	5300	1700	6900	27,200	63,500	177,000 5.06
10	250	3260	2890	2420	2050	9800	5300	1700	6900	25,900	60,500	174,000 4.98
Reacidified Thorex												
0.33	850	6490	7760	11,000	11,700	11,000	16,700	3200	14,600	62,700	146,000	259,000 7.41
1	840	6350	7650	10,600	6700	11,000	16,700	3200	14,600	58,400	136,000	249,000 7.12
3	810	6160	7480	10,100	3400	11,000	16,700	3200	14,600	55,500	129,000	242,000 6.92
10	770	5870	7240	9410	2050	11,000	16,700	3200	14,600	53,200	124,000	237,000 6.78
Thorex glass												
0.33	400	4070	4830	3940	11,700	10,700	7600	1700	7800	49,500	92,200	205,000 5.86
1	390	3970	4760	3810	6700	10,700	7600	1700	7800	35,500	82,900	196,000 5.60
3	380	3820	4620	3620	3400	10,700	7600	1700	7800	32,700	76,300	189,000 5.40
10	360	3620	4450	3360	2050	10,700	7600	1700	7800	31,200	72,800	186,000 5.32

Table 4c. Costs for Ten Years' Storage of Solidified Wastes

Waste Type and Age (yr) at Time of Storage	Excavation (\$/yr)	Concrete (\$/yr)	Epoxy Lining (\$/yr)	Partitions (\$/yr)	Cooling System (\$/yr)	Cranes (\$/yr)	Demineralizer (\$/yr)	Radiation Monitors (\$/yr)	Buildings (\$/yr)	Const. O'head, Eng. and Contingency (\$/yr)	Total Capital (\$/yr)	Total Capital & Operating	
												(\$/yr)	(10 ⁻³ mills/kwh _e)
Acid Purex													
0.33	610	7810	2650	7000	42,000	11,000	11,500	1700	8700	70,000	163,000	276,000	2.84
1	600	7680	2620	6780	27,500	11,000	11,500	1700	8700	58,900	137,000	250,000	2.57
3	580	7440	2570	6500	16,800	11,000	11,500	1700	8700	50,200	117,000	230,000	2.37
10	540	7160	2510	6050	11,000	11,000	11,500	1700	8700	44,800	105,000	218,000	2.24
Reacidified Purex													
0.33	1450	13,100	11,700	21,700	42,000	11,500	27,900	3200	18,300	113,000	264,000	377,000	3.88
1	1410	13,000	11,500	21,000	27,500	11,500	27,900	3200	18,300	101,000	236,000	349,000	3.59
3	1360	12,700	11,300	20,100	16,800	11,500	27,900	3200	18,300	92,000	215,000	328,000	3.38
10	1280	12,200	10,800	18,600	11,000	11,500	27,900	3200	18,300	86,000	201,000	314,000	3.23
Acid Thorex													
0.33	960	9530	8380	12,800	15,500	11,100	18,300	3200	15,100	71,100	166,000	279,000	7.98
1	930	9390	8250	12,300	10,500	11,100	18,300	3200	15,100	66,900	156,000	269,000	7.69
3	900	9160	8080	11,700	6600	11,100	18,300	3200	15,100	62,900	147,000	260,000	7.44
10	850	8830	7820	10,900	4500	11,100	18,300	3200	15,100	60,400	141,000	254,000	7.26
Reacidified Thorex													
0.33	2270	22,900	17,200	36,500	15,500	12,000	45,600	3200	24,400	134,000	313,000	426,000	12.2
1	2220	19,100	17,100	35,500	10,500	12,000	45,600	3200	24,400	127,000	297,000	410,000	11.7
3	2130	18,700	16,600	33,900	6600	12,000	45,600	3200	24,400	122,000	285,000	398,000	11.4
10	1990	18,100	16,000	31,300	4500	12,000	45,600	3200	24,400	118,000	275,000	388,000	11.1
Thorex glass													
0.33	1170	11,100	11,000	16,500	15,500	11,300	22,600	3200	16,500	82,000	191,000	304,000	8.69
1	1130	10,900	9610	16,000	10,500	11,300	22,600	3200	16,500	76,000	178,000	291,000	8.32
3	1090	10,600	9420	15,200	6600	11,300	22,600	3200	16,500	72,500	169,000	282,000	8.06
10	1030	10,300	9120	14,100	4500	11,300	22,600	3200	16,500	69,400	162,000	275,000	7.86

Table 4d. Costs for Thirty Years' Storage of Solidified Wastes

Waste Type and Age (yr) at Time of Storage	Excavation (\$/yr)	Concrete (\$/yr)	Epoxy Lining (\$/yr)	Partitions (\$/yr)	Cooling System (\$/yr)	Cranes (\$/yr)	Demineralizer (\$/yr)	Radiation Monitors (\$/yr)	Buildings (\$/yr)	Const. O'head, Eng. and Contingency (\$/yr)	Total Capital (\$/yr)	Total Capital & Operating	
												(\$/yr)	(10 ⁻³ mills/kwh _e)
Acid Purex													
0.33	1380	9900	10,900	20,600	48,000	11,100	25,400	2500	17,700	110,000	257,000	370,000	3.81
1	1300	9700	10,700	19,900	37,000	11,100	25,400	2500	17,700	101,000	236,000	349,000	3.59
3	1300	9400	10,400	19,000	27,000	11,100	25,400	2500	17,700	93,000	217,000	330,000	3.40
10	1200	9100	10,100	17,700	20,000	11,100	25,400	2500	17,700	86,000	201,000	314,000	3.23
Reacidified Purex													
0.33	3000	22,000	21,700	50,500	48,000	12,500	58,500	2500	28,900	185,000	432,000	545,000	5.61
1	3000	21,800	21,400	49,000	37,000	12,500	58,500	2500	28,900	175,000	409,000	522,000	5.38
3	2800	21,300	20,900	46,900	27,000	12,500	58,500	2500	28,900	166,000	387,000	500,000	5.15
10	2700	20,700	20,200	43,300	20,000	12,500	58,500	2500	28,900	157,000	366,000	479,000	4.93
Acid Thorex													
0.33	1900	13,700	14,300	30,000	17,000	11,600	36,200	2500	21,400	112,000	261,000	374,000	10.7
1	1800	13,400	14,100	29,000	13,000	11,600	36,200	2500	21,400	107,000	250,000	363,000	10.4
3	1800	13,100	13,800	27,500	10,000	11,600	36,200	2500	21,400	103,000	241,000	354,000	10.2
10	1700	12,500	13,300	25,500	7500	11,600	36,200	2500	21,400	99,000	231,000	344,000	9.84
Reacidified Thorex													
0.33	4300	31,600	31,000	70,900	16,000	14,000	85,000	3400	42,000	223,000	521,000	634,000	18.1
1	4200	31,000	30,500	68,600	12,000	14,000	85,000	3400	42,000	217,000	507,000	620,000	17.7
3	4000	30,200	29,900	65,600	9300	14,000	85,000	3400	42,000	212,000	495,000	608,000	17.4
10	3800	29,100	28,800	60,800	6900	14,000	85,000	3400	42,000	205,000	478,000	591,000	16.9
Thorex glass													
0.33	2400	17,400	17,500	38,600	17,000	12,000	46,000	2500	24,700	133,000	311,000	424,000	12.1
1	2300	17,100	17,200	37,300	13,000	12,000	46,000	2500	24,700	129,000	301,000	414,000	11.8
3	2200	16,600	16,800	35,500	10,000	12,000	46,000	2500	24,700	124,000	290,000	403,000	11.5
10	2100	16,000	16,200	33,000	7500	12,000	46,000	2500	24,700	120,000	280,000	393,000	11.2

3.1 Capital Costs

The capital costs of various components, expressed on an annual basis and allowing 4% interest on the investment, are computed by application of the unit costs, amortization periods, and annuity factors given in Table 5 to the design data presented in Tables 2a-2d. A cost of $\$1/\text{yd}^3$ is assumed for excavation, and $\$100/\text{yd}^3$ is used for formed, reinforced concrete. Epoxy lining is applied to the inside surface of the concrete for $\$1.25/\text{ft}^2$ of surface, and $\$5/\text{ft}^2$ of 1/4-in. aluminum plate is used as the installed cost for canal partitions.

Cooling system costs are estimated in a similar manner (described in a previous study).¹ Total capital and operating costs for four systems sized for different maximum heat generation rates were computed (Table 6), permitting the costs for other rates to be obtained by graphical interpolation.

Installed costs of bridge cranes are dependent on the capacity, length of span, length of track, and structural requirements for those mounted overhead in the central canal (Tables 4a-4d). An installed cost of \$400 per gallon per minute of capacity is used for the demineralized water systems,⁵ and radiation monitors are assessed at \$1000 and \$2000, each, for Geiger tube and scintillation detectors, respectively.⁶ Building costs are estimated on the basis of $\$25/\text{ft}^2$ of floor area for masonry construction and $\$5/\text{ft}^2$ for light-construction frame buildings.

Capital costs, expressed as dollars per year, are obtained by multiplying the capital investments of each component by its respective annuity factor, which reflects a 4% interest on the investment over the amortization period. In the cases of 30 years of interim storage (Table 4d), present-worth considerations are used; and they result in a saving of from 20 to 30% in capital costs.* For all waste types except that of reacidified Thorex, it is assumed that two storage canals are built immediately, a third is added after 10 yr, and the fourth after 20 yr. This gives a present-worth factor of 0.782. In the case of the six-canal reacidified Thorex waste facilities, a present-worth factor of 0.717 is used, assuming initial construction of two canals, followed by the addition of the remaining four canals at

* Capital costs include 4% interest on investment.

Table 5. Cost Basis of Facility Components

Component	Unit Cost	Amortization Period (yr)	Annuity Factor at 4% Interest
Excavation	\$1/yd ³	50	0.0465
Concrete	\$100/yd ³	50	0.0465
Epoxy lining	\$1.25/ft ²	10	0.123
Aluminum partitions	\$5/ft ²	25	0.0640
Cooling system	Table 6	20	0.0736
Cranes		25	0.0640
100-ton, overhead on 40-ft track	\$125,000		
5-ton, overhead for central canal	\$ 15,000		
5-ton			
24-ft span	\$ 5,000		
48-ft span	\$ 6,000		
Double track	\$32/ft		
Demineralizer system	\$400/gpm	10	0.123
Radiation monitors		10	0.123
Geiger-tube detectors	\$1,000 ea		
Scintillation detectors	\$2,000 ea		
Buildings		50	0.0465
Central canal, service, office	\$25/ft ²		
Storage canals	\$ 5/ft ²		

Table 6. Cooling System Costs

	Maximum Heat Generation Rate (Btu/hr)			
	3×10^6	10×10^6	30×10^6	70×10^6
Capital Costs				
Cooling tower cost	\$3,300	\$11,100	\$33,000	\$77,000
Heat exchanger surface, ft ²	1540	5050	15,000	38,900
Number of 2000 ft ² units	1	3	7	20
Cost (\$7,000 ea)	\$7,000	\$21,000	\$49,000	\$140,000
Pump duty, gpm	222	750	2220	5000
Number of 1000-gpm units	2	2	6	10
Cost (\$5000 ea)	\$10,000	\$10,000	\$30,000	\$50,000
Total capital investment	\$20,300	\$42,100	\$112,000	\$267,000
Total capital cost per year	\$1,500	\$3,100	\$8,200	\$19,600
Operating Costs				
Power cost per year	\$1,300	\$4,400	\$13,000	\$29,000
Water cost per year	\$600	\$2,000	\$6,000	\$14,000
Total operating cost per year	\$1,900	\$6,400	\$19,000	\$43,000
Total Cost per year	\$3,400	\$9,500	\$27,200	\$62,600

6-yr intervals. Present worth is not used for the central facilities and masonry buildings. The use of present worth in estimating costs of facilities for storage times of 1, 3, and 10 years would have resulted in savings of less than 10%, and was therefore not employed.

To the capital costs of the components, 40% is added for construction overhead, 15% for engineering, and 20% for contingencies. The total capital costs range from \$35,300/yr for 1-yr storage of 10-year-old acid Purex waste to \$521,000/yr for 30-yr storage of 1/3-yr-old reacidified Thorex waste (Tables 4a-4d). This corresponded to total capital investments of \$307,000 and \$4,062,000, respectively.

3.2 Operating Costs

Except for the power and water requirements for the cooling systems, which are considered as part of those costs, the only significant operating costs are for labor. Total yearly labor costs, assumed to be the same for all waste types and for any period of storage, are estimated to be \$113,000 based on 9 man-years at \$12,000 per man-year, including overhead. The manpower breakdown is: four shift operators, three mechanics for maintenance and miscellaneous services, one health physicist, and one supervisor.

3.3 Total Costs

The total costs, representing the sum of capital and operating costs, range from \$148,000 per year for 1-yr storage of 10-yr-old acid Purex waste to \$634,000 per year for 30-yr storage of 1/3-yr-old reacidified Thorex (Tables 4a-4d). The total annual costs are converted to mills/kwh_e by dividing by either 9.72×10^{10} kwh_e/yr or 3.5×10^{10} kwh_e/yr, the electrical power produced from irradiation of uranium converter fuel (Purex waste) and thorium converter fuel (Thorex waste), respectively (Tables 4a-4d and Fig. 5a-5d). Highest costs are for storage of 1/3-yr-old wastes and ranged from 18×10^{-3} mills/kwh_e for 30-yr storage of reacidified Thorex to 1.9×10^{-3} mills/kwh_e for 1-yr storage of acid Purex (Fig. 5a). Lowest costs are for the storage of 10-yr-old wastes, which ranged from 17×10^{-3}

Fig. 5a. Costs of Interim Storage of Solidified Wastes. Age of Wastes: 0.33 yr.

Fig. 5. b Costs of Interim Storage of Solidified Wastes. Age of Wastes: 1 yr.

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Fig. 5. c Costs of Interim Storage of Solidified Wastes. Age of Wastes: 3 yr.

Fig. 5. d Costs of Interim Storage of Solidified Wastes. Age of Wastes: 10 yr.

mills/kwh_e for 30-yr storage of reacidified Thorex to 1.5×10^{-3} mills/kwh_e for 1-yr storage of acid Purex (Fig. 5d). Although costs did decrease with age of waste at time of storage, this effect was not very pronounced, usually amounting to less than a 15% reduction in costs for storage of 10-yr-old wastes, compared with equivalent-length storage of the same wastes aged only 1/3 yr.

3.4 Costs of Combined Waste Storage

The costs for the storage of the combinations of solidified acid Purex-acid Thorex and reacidified Purex-reacidified Thorex in the same facilities are estimated by using the costs computed for handling each waste type separately (Table 7). Capital costs of the facilities, excluding cooling system costs, are estimated on the basis of the total lengths of storage canals required. Cooling system costs for different maximum heat generation rates for wastes 1/3-yr-old at time of storage are obtained as explained in Sec 3.1. Total capital costs, including allowances for construction overhead, engineering, and contingency, are added to an estimated annual operating cost of \$113,000 to give total costs ranging from \$202,000/yr to \$827,000/yr. The latter costs are converted to mills/kwh, using the factor, 1.32×10^{11} kwh_e/yr, the total electrical power produced per year.

Costs of storage of Purex and Thorex wastes together in the same facility range from 1.5×10^{-3} mills/kwh_e for 1-yr storage to 4.8×10^{-3} mills/kwh_e for 30-yr storage for the calcined acid wastes and from 1.8×10^{-3} to 6.3×10^{-3} mills/kwh_e for the calcined reacidified wastes (Fig.6). Storage of acid wastes as solids is cheaper by factors of from 2 to 2.7 than storage of the same wastes as liquids.¹ However, for most storage times, storage of neutralized liquid wastes is slightly cheaper than that of reacidified Purex and Thorex solids.

Table 7. Specifications and Costs for Storage of Purex and Thorex Waste Combinations

Waste Types and Duration (yr) of Storage	Length 48-ft Canal (ft)	Capital Cost Ex- cluding Cooling System (\$/yr)	Cooling System		Const. O'head, Eng. & Contin- gency (\$/yr)	Total Capital Cost (\$/yr)	Total Capital & Operating	
			Max. Heat Evol- tion (10 ⁶ Btu/hr)	Cost (\$/yr)			(\$/yr) (10 ⁻³ mills/kwh _e)	
Acid Purex - Acid Thorex								
1	37	24,000	31.3	27,000	38,200	89,200	202,000	1.53
3	108	46,000	47.6	42,500	66,500	155,000	268,000	2.03
10	362	112,000	63.9	60,000	129,000	301,000	414,000	3.13
30	1083	215,000	92.5	83,000	223,000	521,000	634,000	4.79
Reacidified Purex - Reacidified Thorex								
1	101	43,000	31.3	27,000	52,000	122,000	235,000	1.78
3	300	100,000	47.6	42,500	107,000	250,000	363,000	2.74
10	1002	210,000	63.9	60,000	202,000	472,000	585,000	4.42
30	3005	325,000	92.5	83,000	306,000	714,000	827,000	6.25

Fig. 6. Comparative Costs of Interim Storage of Liquid and Solid Wastes.

4. APPENDIX A

Shielding Calculations

As a basis for calculating the height of water required for shielding from the waste-filled cylinders standing in vertical array, a 6-ft width of canal containing 24-in.-diam cylinders was taken as a radiation source. The choice of a 6-ft width is sufficient to include a double row of cylinders, and the same results would be obtained for a 3-ft width containing 12-in.-diam cylinders or a 1.5-ft width of 6-in.-diam cylinders. By taking a unit length of the 6-ft width large enough to contain several cylinders, the volume fraction of waste material in the slab is about 0.35 and the average specific gravity of the slab is 1.09 for acid waste and 1.38 for neutralized waste.

Source strengths of individual cylinders were calculated previously in obtaining shielding requirements for shipping casks.³ Homogenized source strengths were calculated for the 6-ft width of canal by multiplying individual cylinder strengths by the number of cylinders in a unit length (18 ft was used, containing 12 cylinders) and dividing by the volume of the slab. Energy groups below 1.55 Mev had negligible effect on the shielding requirements. Homogenized source strengths for acid Purex wastes aged 1.4, 9.5, and 31 years are given in Table A.1. Source strengths of the other waste types relative to acid Purex were 0.395, 0.237, 0.0800, and 0.182 for reacidified Purex, acid Thorex, reacidified Thorex, and acid Thorex glass, respectively.

The dose at the surface of the canal water was calculated by using the following equation for infinite slab geometry:⁷

$$\phi = \frac{\beta S_v}{2\mu_s} \left[E_2(b_1) - E_2(b_3) \right],$$

where ϕ = gamma flux, photons $\text{sec}^{-1} \text{ cm}^{-2}$,

β = build up factor,

S_v = source strength, photons $\text{sec}^{-1} \text{ cm}^{-3}$,

Table A.1 Homogenized Source Strengths for Acid Purex Waste
as a Function of Age

Average Energy (Mev)	Source Strength, S_v (photons $\text{sec}^{-1} \text{ cm}^{-3}$)		
	1.4 yr	9.5 yr	31 yr
1.55	2.12×10^9	2.46×10^8	3.79×10^7
1.99	2.46×10^8	1.90×10^7	3.12×10^5
2.38	5.08×10^8	3.94×10^7	7.29×10^5
2.75	1.18×10^8	1.32×10^6	9.66×10^1

μ_s = attenuation coefficient for the source, cm^{-1} ,

$$E_2(b) = b \int_b^{\infty} \frac{e^{-t}}{t^2} dt ,$$

$$b_1 = \mu t ,$$

$$b_3 = b + \mu_s h ,$$

μ = attenuation coefficient of shield, cm^{-1} ,

t = shield thickness, cm ,

h = source thickness, cm .

Ratios of attenuation coefficient to density were obtained from Blizard,⁸ and are 0.0576, 0.0493, 0.0453, and 0.0420 cm^2/gm for energy groups 1.55, 1.99, 2.38, and 2.75 Mev. Buildup factors, which are functions of b , and energy, were also taken from Blizard. Values of E_2 were obtained from graphs in Rockwell.⁷ The calculated fluxes at the canal surface were converted to dose rates by:

$$D = 2\phi E \times 10^{-6} ,$$

where D = dose rate, roentgens/hr ,

E = energy, Mev.

Calculated dose rates as functions of water depth above the tops of the cylinders are shown in Figs. A.1-A.3.

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Fig. A. 1 Dose Rate at the Canal Surface as a Function of the Depth of Water to the Cylinder Tops. Waste Age: 1.4 yr.

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Fig. A. 2 Dose Rate at the Canal Surface as a Function of the Depth of Water to the Cylinder Tops. Waste Age: 9.5 yr.

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Fig. A. 3 Dose Rate at the Canal Surface as a Function of the Depth of Water to the Cylinder Tops. Waste Age: 31 yr.

5. APPENDIX B

Heat Generation Rates

In estimating cooling system requirements for the interim storage of liquid wastes, heat generation rates were calculated during accumulation of the waste stream (with radioactive decay taking place concurrently) and during dead storage (after accumulation had stopped).¹ These same results are plotted in Fig. B.1, with the length of dead storage shown as a parameter. In the liquid-storage study, economically optimum fractions of accumulation and dead times were found to be:

<u>Interim Liquid Storage Period (yr)</u>	<u>Accumulation Period (yr)</u>	<u>Dead Period (yr)</u>
1	0.67	0.33
3	1.6	1.4
10	3.4	6.6

Thus, the waste accumulated in a solid storage system will previously have undergone a period of accumulation and a period of dead storage as liquids. Maximum heat generation rates for solid storage were approximated from Fig. B.1 by choosing the average dead time of the waste entering the solid storage facility. In the case of Purex waste, for example, if the waste has undergone 10 yr of interim liquid storage, the first pots entering a facility for 3 yr of interim storage as solids would have undergone 6.6 yr of dead storage and the last pots, 9.6 yr of dead storage. Thus, the average dead storage time would be 8.1 yr, and a heat generation rate of 4.5×10^6 Btu/hr is read from Fig. B.1; but, this represents 3.4 yr of accumulation in the liquid system, while the solid system contains only 3.0 yr of accumulation. Multiplying by the factor $3.0/3.4$ yields 3.97×10^6 Btu/hr, the maximum heat generation rate in this facility. This procedure assumes a straight-line decay curve for the waste in the solid storage facility, which is on the conservative side and sufficiently accurate for the purpose of this report.

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Fig. B. 1 Heat Generation Rate for Interim Liquid Storage of Purex Waste as a Function of Accumulation Time and Dead Storage Time.

The maximum heat generation rates for the storage of solidified Thorex wastes were found by multiplying the rates computed for Purex waste by the factor 0.36. This factor was obtained from the ratios of the annual fuel processing rates and the burnups, as follows:

$$\frac{270 \text{ tons/yr thorium}}{1500 \text{ tons/yr uranium}} \times \frac{20,000 \text{ Mwd/ton}}{10,000 \text{ Mwd/ton}} = 0.36 .$$

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